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WELDING CHARACTERISTICS OF 12NI-5CR-3MO MARAGING STEEL — I

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By L. P. Connor and A. M. Rathbone

Approved by J. H. Gross, Division Chief

Abstract

As part of the program to determine the feasibility of developing a high-yield-strength hull weldment in the range 180 to 210 ksi, maraging-steel base metals have been extensively evaluated. To acquire background information on the welding characteristics of such steels, the mechanical properties of the weld-heat-affected zone in a 12Ni-5Cr-3Mo maraging steel were determined.

Results of tension and impact tests (after aging) on simulated weld-heat-affected-zone microstructures indicated that the tensile properties of the structures were not adversely affected by the weld-thermal cycles, but that the various structures exhibited a moderate general loss in toughness (4 to 14 ft-lb at +80 F) from that of the unwelded plate (45 ft-lb at +80 F). The austenite contents of the various heat-affected-zone regions ranged from 0 to 10 percent, the largest amount being present in the region heated to 1200 F. The results of metallographic examinations indicated that the weld-heat-affected zone is composed of regions of underaged martensite, properly aged martensite, and regions containing mixtures of underaged and overaged martensite with some retained austenite.

The results of this study indicate that the mechanical properties of the heat-affected-zone in the 12Ni-5Cr-3Mo maraging steel are slightly poorer than those of the unwelded plate, but may be adequate if the original toughness of the base plate is high enough. However, before final conclusions concerning the base-metal weldability of 12Ni-Cr-Mo maraging steels can be drawn, the following work must be completed: (1) a determination of heat-affected-zone crack susceptibility, (2) additional impact tests of heat-affected zones in higher toughness base plates, and (3) determinations of the effect of retained, or reverted, austenite on corrosion and fatigue properties.

Introduction

As part of the program to determine the feasibility of developing a hull weldment having a yield strength in the range 180 to 210 ksi, maraging-steel base metals have been extensively evaluated.[1,2,3)*] Generally, the results of the base-metal evaluations indicated that some maraging steels exhibit good combinations of yield strength and notch toughness, whereas many apparently similar maraging steels exhibit poor combinations. Although the cause for these observed variations in mechanical properties is not completely understood at present, the maraging approach to high strength steels is considered quite promising.

To acquire background information on the welding characteristics of maraging steels, a program was undertaken to evaluate the mechanical properties of simulated weld-heat-affected zones in production plates of one of the most promising maraging steel compositions, a 12Ni-5Cr-3Mo type. The present report describes the results of that study.

Materials and Experimental Work

Materials

The welding study was performed on 1/2-inch-thick plate (No. 59807E) produced from a Duquesne Works' 20-ton basic-electric-furnace heat (No. X14689) that was subsequently rolled and heat-treated at the

*See References.

Homestead District Works. (The processing procedures used to produce the plate have been described previously.)[2] The plate was mill heat-treated as follows: solution-annealed at 1500 F for 1 hour, water-quenched, aged at 900 F for 3 hours, and water-quenched. The chemical composition and mechanical properties of the plate are shown in Table I.

Experimental Work

The RPI Gleeble device previously described[4] was used to synthetically reproduce microstructures corresponding to various regions throughout the weld-heat-affected zone. The conditions corresponding to the simulated microstructures are listed in Table II. To obtain an estimate of the mechanical properties of the composite heat-affected zone, microstructures were reproduced in specimens heated to 8 peak temperatures ranging from 2400 to 1000 F (with constant heat input, plate thickness, and preheat temperature). In addition, to obtain an estimate of the effect of slow cooling, one specimen was produced by using a preheat temperature of 300 F.

For each weld-thermal cycle, seven specimen blanks were synthetically heat treated in the Gleeble device to obtain the appropriate microstructures. After the heat treatment, the hardness (Rockwell C) of each blank was determined in the "as-welded" condition, and then each blank was aged at 900 F for 3 hours and water-quenched. After aging, four of the seven blanks were machined into Charpy V-notch impact

specimens, and duplicate specimens were subsequently tested at +80 F and 0 F. Two of the seven blanks were machined into "transversely welded"* 0.252-inch-diameter tension-test specimens and subsequently tested at room temperature. The remaining sample for each condition was examined metallographically and its retained austenite content was determined by X-ray diffraction.

Results and Discussion

Mechanical Properties of the Heat-Affected Zone

A summary of the results of the tests on the specimens containing simulated heat-affected-zone microstructures is shown in Table III; the results of the tension and impact tests are shown graphically in Figure 1. After aging at 900 F for 3 hours, the yield strength of the various heat-affected-zone microstructures ranged from 185 to 202 ksi, whereas that of the unwelded base plate was 190 ksi. The grain-coarsened region (2400 F peak temperature) exhibited a yield strength slightly lower than that of the unwelded base plate, whereas all other heat-affected-zone regions overmatched the base-metal yield strength. As shown in Figure 1, the yield strength decreased in the overaging temperature range (1000 to 1200 F), increased as solution annealing proceeded (1200 to 1600 F), and then decreased sharply at solution-annealing temperatures of 2000 and 2400 F. The yield strength of

*The tension-test specimens contained the simulated microstructure in the center of the reduced section and thereby resembled a transverse-tension test (or joint-efficiency test) of a butt weld.

unwelded base plate has also been observed[2] to decrease as the solution-annealing temperature is increased. The specimens that were cooled slowly (2000 F peak temperature and 300 F preheat temperature) exhibited tensile properties similar to those specimens that were cooled relatively fast (2000 F peak temperature and 78 F preheat temperature). Thus, the effect of slow cooling on the tensile properties of the weld-heat-affected zone appears to be small. Generally, the results of the tension tests indicate that the weld-heat-affected-zone microstructures were not adversely affected by the weld-thermal cycle.

The results of the impact tests on the various weld-heat-affected-zone microstructures show that the Charpy V-notch energy absorption varied inversely with the yield strength and was in the range 31 to 41 ft-lb. The toughness of the unwelded base plate was 45 ft-lb. The practical significance of this moderate general loss in weld-heat-affected-zone toughness is not known at present. If this loss in toughness is an absolute effect and the base plate toughness was in the range 60 to 70 ft-lb (+80 F), then the observed heat-affected-zone toughness loss would probably be insignificant.

The results of the hardness measurements are shown graphically in Figure 2. Comparison of the hardness values before aging with those after aging shows that the "as-welded" heat-affected-zone microstructures corresponding to peak temperatures in the range 1300 to 2400 F

consisted of soft, or "solution-annealed," martensite (Rockwell C hardnesses of 30 to 31). The "as-welded" microstructures corresponding to peak temperatures in the range 1000 to 1300 F gradually decreased from the original hardness of the aged unwelded base plate to that of the solution-annealed material as the martensite of the aged base plate was gradually transformed to austenite. On the basis of the hardness measurements, the lower transformation temperature (upon rapid heating) would appear to be about 1000 F (or somewhat lower), whereas the upper transformation temperature (upon rapid heating) would appear to be about 1300 F.

The austenite contents of the various heat-affected-zone microstructures after aging ranged from 0 to 10 percent, Table III, the largest amount being observed in the region heated to 1200 F. The occurrence of retained austenite in the regions heated from 1300 to 1600 F (regions completely austenitized during heating) indicates that the austenite heated to these temperatures was probably inhomogeneous. The fact that no retained austenite was observed in the regions heated to 2000 and 2400 F indicates that at these higher temperatures the austenite became more homogeneous. Generally, the austenite detected in the simulated microstructures did not appear to have a deleterious effect on the tensile and impact properties; however, its effect on other properties (fatigue, corrosion, etc.) is not presently known.

Metallographic Examination

For comparative purposes, a typical microstructure of solution-annealed and aged 12Ni-5Cr-3Mo maraging base metal is shown in Figure 3. Simulated weld-heat-affected-zone microstructures for each condition of simulation (except the 1300 F peak temperature) are shown in Figures 4, 5, and 6. The microstructure produced upon heating to 2400 F, Figure 4A, evidences grain coarsening and pronounced etching of the prior austenite grain boundaries. Some slight amount of peppery precipitate is present in the matrix; however, the fact that the matrix generally appears unaffected by the etchants is indicative of underaging. The drop in yield strength at the high peak temperatures indicates that the microstructures have not responded completely to the aging reaction. However, because the hardness after aging was 41 Rockwell C, which is close to the maximum attainable, it is postulated that the aging reaction(s) involves coherent and then incoherent precipitation and that the reaction product(s) in the 2400 F peak temperature microstructure is a coherent precipitate(s). It is further postulated that the residual stresses associated with coherency lower the yield strength without significantly affecting the tensile strength (hardness). The microstructure produced upon heating to 2000 F, Figure 4B, appears similar to the 2400 F microstructure except that the prior austenite grains are smaller and the grain boundaries are not etched quite so

deeply. The microstructure of material heated to 2000 F and cooled slowly (300 F preheat temperature), Figure 4C, exhibits less prior austenite grain-boundary etching and more peppery precipitate than the one cooled rapidly (78 F preheat temperature).

The microstructures formed upon heating to 1600 and 1400 F are shown in Figures 5A and 5B, respectively. The 1600 F microstructure exhibits slight light and dark etching bands and indicates that the austenite was slightly inhomogeneous. However, since the 1600 F microstructure appears similar to the microstructure of the unwelded base plate, Figure 3, it appears that this region of the heat-affected zone has undergone an optimum aging response. Unexpectedly, the 1400 F microstructure evidences slight banding and no dark etching regions. Apparently, the 1400 F region did not age as rapidly as the 1600 F region.

The microstructures produced upon heating to 1200, 1100, and 1000 F are shown in Figures 6A, 6B, and 6C, respectively. The three microstructures exhibit light and dark bands, the amounts of dark etching constituent decreasing as the temperature is lowered. The dark etching areas are probably "overaged" regions.

Generally, the results of the metallographic examinations indicate that the weld-heat-affected zone in the 12Ni-5Cr-3Mo maraging steel is composed of regions of underaged martensite, properly aged

martensite, and regions containing mixtures of underaged and overaged martensite and some stable retained austenite. Because the maraging steels contain large quantities of alloying elements, the rapid thermal cycles involved in welding would probably cause more inhomogeniety in the weld-heat-affected-zone in a maraging steel than that observed in lower alloy steels.

Summary

The weld-heat-affected-zone microstructures of a 12Ni-5Cr-3Mo maraging steel were simulated, and the mechanical properties of the simulated microstructures were determined. The results may be summarized as follows:

1. Results of tension tests (after aging) on simulated weld-heat-affected zone microstructures showed that the yield strength of the various structures ranged from 185 to 202 ksi and that of the unwelded base plate was 190 ksi. Generally, these tension-test results indicated that the structures were not adversely affected by the weld-thermal cycle.

2. Results of Charpy V-notch impact tests (after aging) on the various weld-heat-affected-zone microstructures showed that the structures exhibited a moderate general loss in toughness ranging from 4 to 14 ft-lb at +80 F. (The toughness of the unwelded base plate was 45 ft-lb at +80 F.)

3. From the results of the aforementioned tension and impact tests, it also appeared that the effect of slow cooling on the toughness and strength of the heat-affected zone was small.

4. Hardness measurements before and after aging indicated that upon rapid heating, the lower and upper transformation temperatures of the 12Ni-5Cr-3Mo steel were about 1000 and 1300 F, respectively.

5. The results of X-ray measurements indicated that the austenite content of the various heat-affected-zone structures ranged from 0 to 10 percent, the largest amount being observed in the region heated to 1200 F.

6. The results of metallographic examinations indicated that the weld-heat-affected zone in the 12Ni-5Cr-3Mo maraging steel (after aging) was composed of regions of underaged martensite, properly aged martensite, and regions containing mixtures of underaged and overaged martensite with some retained austenite.

Future Work

General conclusions concerning the weldability of 12Ni-5Cr-3Mo maraging steel cannot be reached until the following work has been completed:

1. A determination of the crack susceptibility of the weld-heat-affected zone.

2. Additional impact tests on simulated weld-heat-affected-zone microstructures in base plates having Charpy V-notch impact values in the range 60 to 70 ft-lb at +80 F.

3. Additional mechanical-property tests on heat-affected-zone microstructures formed upon slow cooling.

4. Determinations of the effect of retained, or reverted, austenite on the corrosion and fatigue properties of maraging steel.

References

1. A. J. Birkle and L. F. Porter, "The Effect of Variations in Titanium, Aluminum, and Molybdenum on the Strength and Toughness of 18Ni-8Co-Mo Maraging Steels," Applied Research Laboratory Progress Report 40.18-002(6), (S-21104-3), September 30, 1963.

2. A. J. Birkle, D. S. Dabkowski, and L. F. Porter, "Exploratory Studies of 180/210 Ksi Yield-Strength Maraging Steels," Applied Research Laboratory Progress Report 40.18-002(10), (S-21104-4), January 2, 1964.

3. A. J. Birkle, D. S. Dabkowski, L. F. Porter, and G. R. Speich, "An Electron-Metallographic Study of Embrittlement in an 18Ni-8Co-Mo Maraging Steel," Applied Research Laboratory Progress Report 40.18-002(5), (S-21104-2), September 27, 1963.

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Table I

Chemical Composition and Mechanical Properties of 1/2-Inch-Thick Plate of 12Ni-5Cr-3Mo Maraging Steel Investigated

Chemical Composition—Percent
(Check Analysis)

Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	Ti	Al*	B	Zr	N	O
X14689	0.023	0.088	0.004	0.008	0.022	12.1	5.21	2.86	0.24	0.38	0.0037	0.01	0.009	0.001

Longitudinal Mechanical Properties**

Tensile Properties				Charpy V-Notch Impact Properties	
Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Energy Absorption, ft-lb +80 F	Energy Absorption, ft-lb -80 F
190	193	13.5	61	45	41

*Acid soluble.
**Results are the average of two tests.

Table II

Welding Conditions Corresponding to Simulated
Weld-Heat-Affected-Zone Microstructures of Test Specimens

Simulated Welding Heat Input, joules/inch	Peak Temperature, F	Simulated Plate Thickness, inch	Preheat Temperature, F
47,000	2400	1/2	78
47,000	2000	1/2	78
47,000	2000	1/2	300
47,000	1600	1/2	78
47,000	1400	1/2	78
47,000	1300	1/2	78
47,000	1200	1/2	78
47,000	1100	1/2	78
47,000	1000	1/2	78

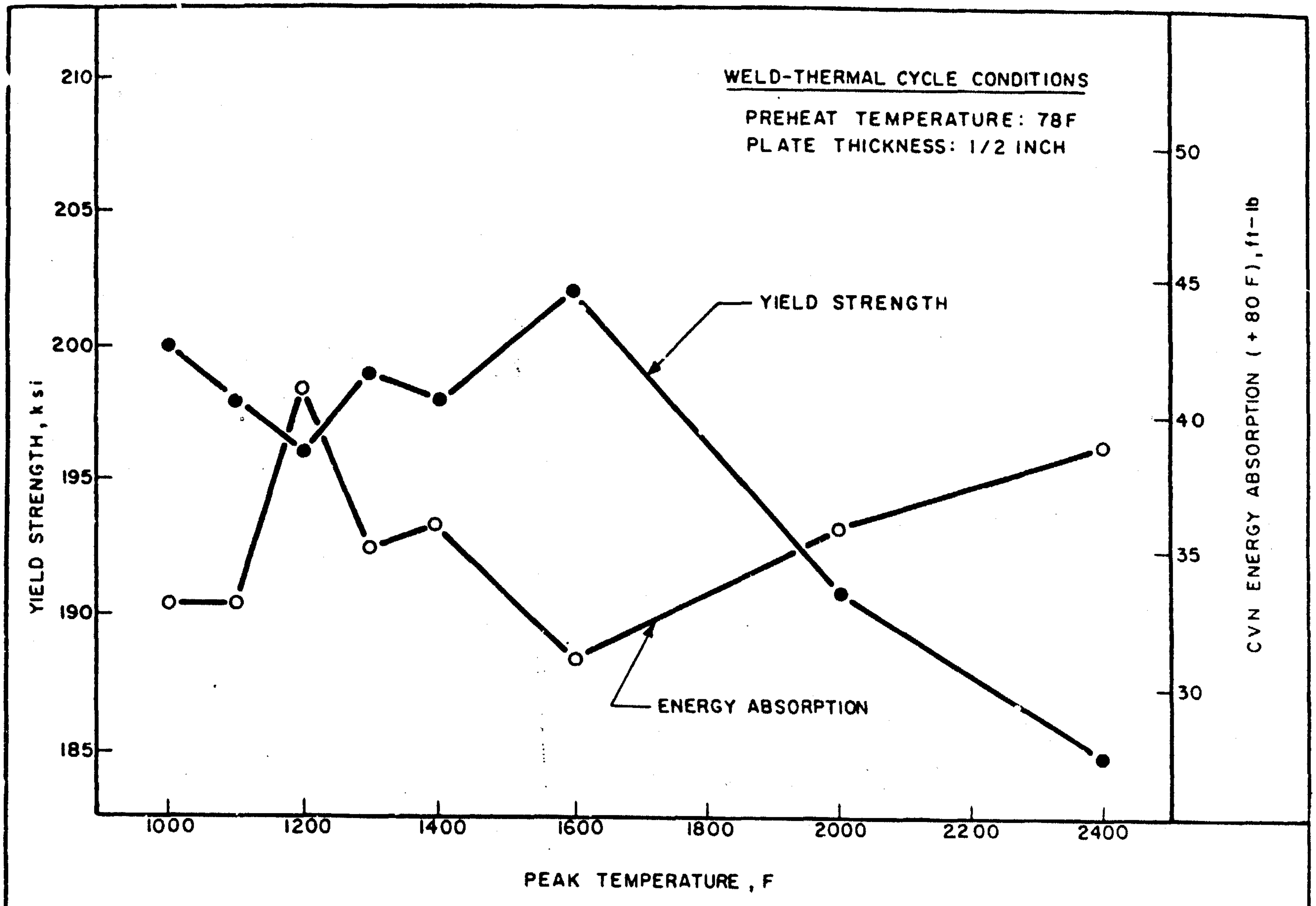
Table III

Mechanical Properties After Aging of Synthetic Heat-Affected-Zone Microstructures of 12Ni-5Cr-3Mo Maraging Steel (Heat No. X14689)

Peak Temp, F	Preheat Temp, F	Austenite Content, %*	Rockwell C Hardness, Before Aging	Rockwell C Hardness, After Aging	Tensile Properties: Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Fracture Location**	Charpy V-Notch Impact Properties: Energy Absorption, ft-lb, +80 F	Energy Absorption, ft-lb, 0 F	Shear Fracture, %, +80 F	Shear Fracture, %, 0 F
2400	78	0	31.5	41.0	185	197	13.2	64.0	HAZ	39	36	100	100
2000	78	0	31.5	41.5	191	200	13.0	61.0	HAZ	36	33	100	100
2000	300	0	31.5	41.5	195	203	12.0	59.0	BM	35	31	100	100
1600	78	6	30.0	42.0	202	203	12.5	59.0	BM	31	32	100	100
1400	78	5	30.0	41.5	198	202	13.5	62.0	HAZ	36	33	100	100
1300	78	4	30.5	42.0	199	202	11.5	57.0	BM	35	31	100	100
1200	78	10	33.0	41.5	196	196	12.8	61.0	HAZ	41	39	100	100
1100	78	6	36.5	41.5	198	200	11.8	61.0	HAZ	33	34	100	100
1000	78	6	40.5	42.0	200	204	13.5	62.0	BM	33	34	100	100

* The austenite content was determined by X-ray diffraction.

** HAZ - means heat-affected zone;
BM - means base metal.



RELATION OF YIELD STRENGTH AND CVN ENERGY ABSORPTION TO PEAK TEMPERATURES IN THE WELD-HEAT-AFFECTED ZONE

DRAWN BY	CHK'D BY	APPROVED BY		
G.A.Z.	A.M.R.	J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO 1
DRAWING NO. ARL 18-223		PROJECT NO 40.018 — 002 (12)		
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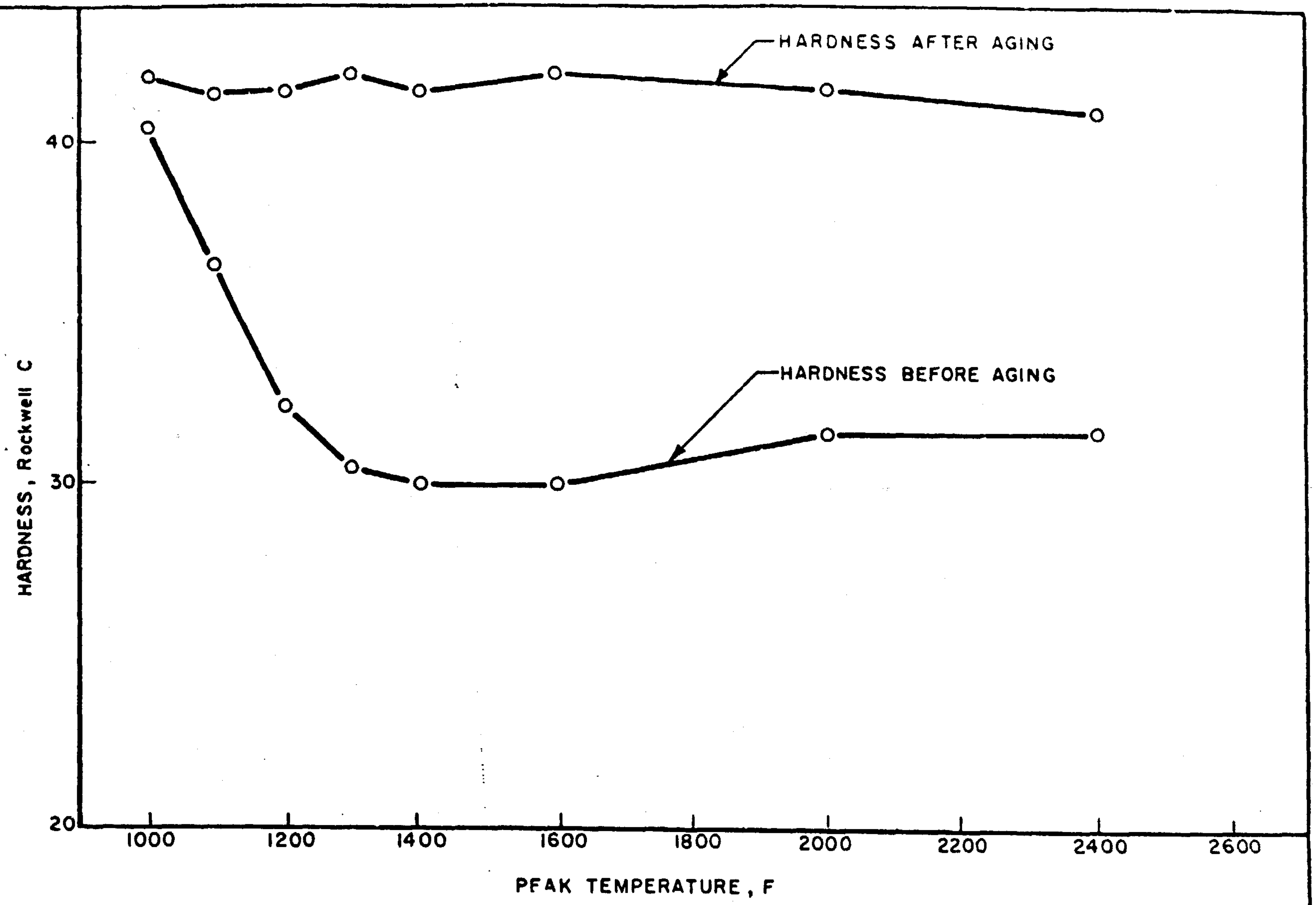

HARDNESS BEFORE AND AFTER AGING AS A FUNCTION OF PEAK TEMPERATURE

DRAWN BY	CHK'D BY	APPROVED BY	UNITED STATES STEEL CORPORATION	FIGURE NO.
G. A. Z.	A. M. R.	J H G	APPLIED RESEARCH	2
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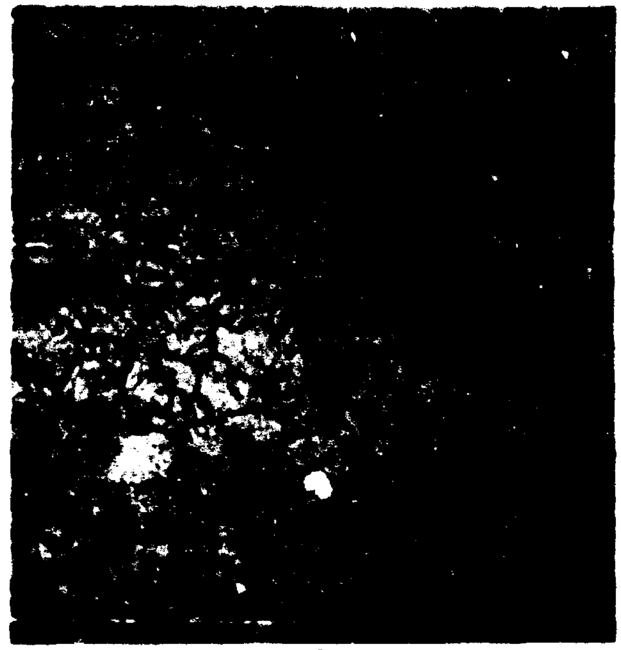
Figure 3. Typical microstructure of unwelded 12Ni-5Cr-3Mo maraging steel. Solution-annealed at 1500 F for 1 hour and aged at 900 F for 3 hours. Ferric chloride and Vilella's reagent. X500.

A. 2400 F peak temperature.
78 F preheat temperature.



B. 2000 F peak temperature.
78 F preheat temperature.

C. 2000 F peak temperature.
300 F preheat temperature.

Figure 4. Simulated heat-affected-zone microstructures in 12Ni-5Cr-3Mo maraging steel—1/2-inch-thick plate and 47,000 joules/inch heat input. Aged at 900 F for 3 hours. Ferric chloride and Vilella's reagent. X500.

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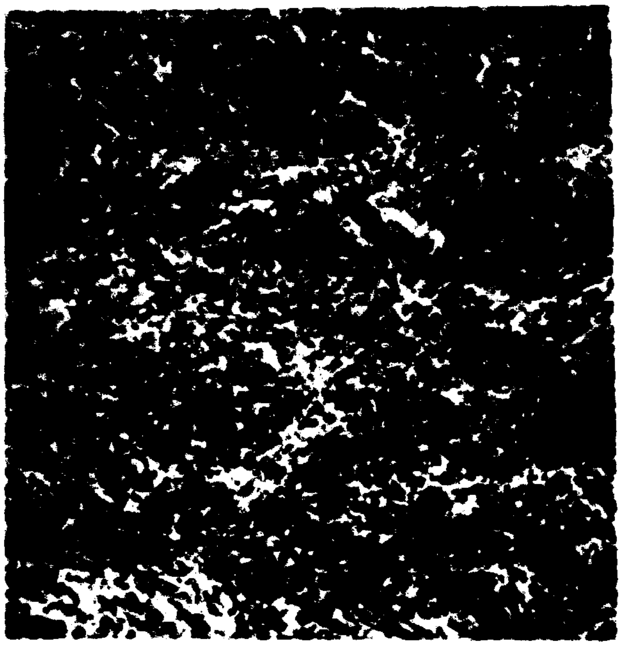

A. 1600 F peak temperature.
78 F preheat temperature.

B. 1400 F peak temperature.
78 F preheat temperature.

Figure 5. Simulated heat-affected-zone microstructures in 12Ni-5Cr-3Mo maraging steel—1/2-inch-thick plate and 47,000 joules/inch heat input. Aged at 900 F for 3 hours. Ferric chloride and Vilella's reagent. X500.

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Figure 5A, B

A. 1200 F peak temperature.
78 F preheat temperature.

B. 1100 F peak temperature.
78 F preheat temperature.

C. 1000 F peak temperature.
78 F preheat temperature.

Figure 6. Simulated heat-affected-zone microstructures in 12Ni-5Cr-3Mo maraging steel—1/2-inch-thick plate and 47,000 joules/inch. Aged at 900 F for 3 hours. Ferric chloride and Vilella's reagent. X500.

2-9264B-1
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